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CLASSIFICATION OF CRYOCOOLERS

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A great diversity of methods and mechanisms have been devised to effect cryogenic refrigeration.

This paper reviews some of the basic parameters and considerations affecting the selection of a particular system.

A classification scheme for mechanical cryocoolers is presented. An important distinguishing feature is the incorporation or not of a regenerative heat exchanger, of valves, and of the method for achieving a pressure variation.

Key words: Cryocoolers; mechanical refrigerators, regenerative heat exchanger.

1. Introduction

A cryocooler is a refrigerating system capable of achieving temperatures in the cryogenic range, generally reckoned to be less than 120K. The word cryogenic is derived from the Greek "icy cold".

Cryocoolers are often rated by their available refrigeration capacity measured in watts. To be meaningful however it is necessary to specify not only the refrigeration capacity but also the temperature at which the refrigeration is available. A cryocooler having a capacity of 1 watt at 4K (liquid helium temperature) is very much different to the cryocooler having a capacity of 1 watt at 80K (liquid nitrogen temperature).

Another important parameter is the power input or work required to achieve refrigeration.

The coefficient of performance of a refrigerator is defined as the ratio:

$$\text{COP} = \text{Refrigeration Capacity} / \text{Power Input or Heat Lifted/Work Done}$$

The ideal coefficient of performance is the Carnot value:

$$\text{COP (Carnot)} = T_E / (T_C - T_E)$$

where T_E = minimum cycle temperature (usually the refrigeration temperature)
 T_C = maximum cycle temperature (generally the atmosphere temperature)

The ratio of the actual coefficient of performance to the Carnot coefficient of performance is sometimes called the efficiency. It is a useful measure of the way an actual machine measures up to the thermodynamic ideal machine. Thus:

$$\begin{aligned} \text{Efficiency} &= \text{Actual COP} / \text{Carnot COP} \\ &= \text{Refrig Cap} / \text{Power Input} \times (T_C - T_E) / T_E \end{aligned}$$

The efficiency of presently available cryocoolers ranges from a minimum of less

than 1 percent to a maximum of near 50 percent. Strobridge (1974) presented "experience" charts for 140 different cryocoolers with the above efficiency variations.

The small machines used for electronic applications have the lowest efficiencies. This is because nearly all the refrigeration generated is consumed in cooling, and maintaining cold, the low temperature region of the machine itself. The surplus or useful refrigeration available from these units is very small; only fractions of a watt are required. Applications requiring a larger useful refrigeration load use systems bigger in size and tending to be more efficient. The highest efficiencies are found in large machines used for liquefiers and range from 20 to 50 percent of the Carnot value.

Other significant parameters for cryocoolers include the total mass and volume of the system and the mass and volume of the cold region. This latter is of particular importance in infra red (I-R) missile guidance or night vision systems with cooled detectors and associated optical/electronic systems mounted in swiveling gimbals. A low mass and volume is necessary to facilitate a fast response with low inertia.

Cool-down time, the period necessary for the machine to achieve stable operation at the design condition following startup is important in some applications of miniature systems, usually weapons related. The combination of a quick cool-down and a slow warmup is a particularly challenging requirement involving mutually opposed high and low 'thermal masses'. Cool-down is sometimes accelerated by operating at a high pressure or speed on startup and later switching to the normal operating mode.

Mechanical vibration and electro-magnetic emissions in the cold region are often important characteristics of cryocoolers. Some applications require the total elimination of any mechanical or electro-magnetic noise. This is best approached by

- a) physical separation of the cold region and the compressor unit where large power input and heat transfers take place
- b) elimination of moving parts in the cold region
- c) the use of plastic, ceramic or other non-magnetic parts in the cold region.

Operating life is another important characteristic often quoted as the mean time before failure (m.t.b.f.) or the mean time before maintenance (m.t.b.m.). This is generally taken to mean the average time of operation before failure (or maintenance) of a number of identical cryocoolers operating under similar conditions. Reliable data for m.t.b.f. and m.t.b.m. based on the accumulated experience of users is very hard to come by. There appears to be no properly organized system for data collection, reduction, rationalization and distribution. Operating life is affected to a large extent by the nature of the system used: Moving parts, sliding seals, bearings, piston rings, etc. wear and generate detritus with deleterious effects on valves, and small passages. Sometimes questions of lubricated versus unlubricated parts involve the balancing in increased wear against the possibilities of contamination of lubricant. Reliability can often be improved by incorporating excess capacity so that operation is intermittent or by the provision of redundant systems.

The shelf life of a cryocooler is frequently important. This is the interval a unit may be required to maintain the capability for operation while standing unused or in occasional intermittent use. Many systems involve mechanical units containing high pressure helium and equipped with a variety of sealed flanges,

shaft seals, screwed fittings etc. Hermetic sealing by seal welding is the best approach to ensure a long shelf life but this of course is not possible for a mechanical unit with dynamic seals.

In split systems where the cold region is separated from the power input unit the nature of the leads connecting the two elements is important. Some systems have flexible leads, others are inflexible. Sometimes they are cold, sometimes at ambient temperature, sometimes a single lead with a cyclic fluctuating pressure, sometimes twin leads with a high pressure feed line and a low pressure return. All these affect the insulation required, the forces and bending moments imposed on gimballed units, the transmission of mechanical, vibration, thermal conduction and pressure attenuation or phasing effects.

Cost, of course, is always important, more so in some cases than others. Separate consideration of capital cost and operating cost including scheduled maintenance and unscheduled maintenance or replacement is necessary. Sometimes the lack of opportunity or possibility for maintenance (space systems) justify increase in the capital cost by the provision of redundant systems or the use of a large, lightly loaded, slow running unit.

The power supplied to drive the cryocooler is eventually degraded to heat and must be rejected from the system. Thus the cooling system to carry the waste heat is an important feature of the cryocooler. Liquid cooling is more efficacious than air or gas cooling because of high heat transfer coefficients and heat capacities achieved with liquids. Air cooling is attractive on grounds of simplicity to almost everyone concerned except those actually responsible for the cooling system. Frequently miniature machines are air cooled but are then located in a pod along with other heat emitting power equipment so the environmental temperature is increased. This complicates the cooling problem. The range of environmental temperature over which the equipment is required to operate ranges from -40°C to as much as 60°C . This in itself presents problems which are compounded in many cases by the further requirement that the refrigeration temperature is a precise value having a tolerance as slight as $+ \text{ or } - 0.1^{\circ}\text{C}$.

System cooling and heat rejection presents special problems in space applications. All the heat must ultimately be rejected by radiation. The well-known equation:

$$Q = EA T^4$$

where Q = radiation heat flux
 E = surface emissivity
 A = area of emitter
 S = Stefan - Boltzman constant
 T = temperature of emitter

clearly dictates a high temperature. However the coefficient of performance equations

$$\text{COP} = T_E / (T_C - T_E)$$

dictate the lowest possible maximum cycle temperature, T_C , (corresponding to T in the above radiation equation).

Continuing with the special requirements for aerospace cryocoolers important characteristics are the ability to withstand the high acceleration and vibration spectrum of a rocket launch, the ability to operate in any orientation and in a zero or low gravity regimen. Reliability and long-life assume an importance not found elsewhere.

2. Classification of cryocoolers

There are many military, civil, medical, and scientific applications for cryocoolers in electronic, space, and defense-related systems. These needs, with the multifarious and diverse requirements enumerated above, have, over the past 40

years, attracted the attention of ingenious and resourceful engineers and scientists. The result is an enormous literature and a wide range of different systems and solutions. Walker (1983) has recently summarized the situation and provided an extensive bibliography and a guided introduction to the field.

The ultimate refrigerator has not yet been invented. This would produce whatever refrigeration was required at the appropriate temperature, would be compact, lightweight and run forever with no maintenance on a pennyworth of kerosene without vibration, noise, or smell. All practical machines are essential compromises of conflicting requirements with particular features emphasized as specified by the client for their application.

The classification chart shown in Figure 1 represents one attempt to clarify a confusing situation. The chart is limited to mechanical cryocoolers producing cryogenic refrigeration by compression and expansion of gases including liquefaction of gases at low temperature. It does not include any of the solid state refrigerators or those customarily confined to temperatures below 3K.

2.1 Regenerative heat exchanger

With the above sweeping limitation in mind the first question to ask when confronted with an unknown cryocooler is:

"Does it have a regenerative heat exchanger".

All types of heat exchangers may be broadly classified into regenerative or recuperative heat exchangers. Recuperative exchangers are equipped with separate flow passages for the two or more fluids involved. The passages are usually contained in conduits with solid walls and the fluids flow continuously. Most heat exchangers are the recuperative type. Regenerative exchangers contain a porous matrix of finely divided material, granules, balls, wires, etc. The fluids flow through the matrix in cyclic succession so the cold blow follows the hot blow, etc. The matrix acts as a thermodynamic sponge alternately releasing heat to the cold fluid and receiving heat from the hot fluid.

The unknown cryocooler will almost invariably include one or more recuperative heat exchangers but if there is no regenerative exchanger it will belong to the group of cryocoolers shown in the upper right-hand box of Figure 1. Claude, Linde-Hampson, Joule-Thomson or Joule-Brayton. These are the names of the originators of the thermodynamic cycles on which these various systems work. They all operate with compression of the working fluid at high temperature, expansion at low temperature, and incorporate counter flow, recuperative heat exchangers. Expansion engines are included in the Claude and Joule-Brayton systems.

2.2 Valves

If the specimen cryocooler does include a regenerative exchanger the next question is:

"Does it have any valves to regulate the flow of the working fluid".

If the unit does include valves as well as a regenerator it will be an Ericsson engine of the type shown in the mid-left box, Solvay, Postle and Gifford-McMahon. The distinction between Solvay and Postle machines is that the Solvay unit includes a work-producing low temperature expansion machine. The Postle unit operates with a displacer only. Gifford and McMahon invented the machines carrying their names in the late 1950's but both their inventions were actually reinventions of the Postle and Solvay engines of the previous century.

2.3 Compressor

If the specimen cryocooler contains a regenerative heat exchanger but no valves the next step in classification is the type of device used to achieve a pressure variation.

Stirling engines incorporate a mechanical compressor so the total enclosed volume of the working space varies cyclically usually as the result of the motion of a piston in a cylinder.

In Vuilleumier engines there is no piston but simply a displacer moving working fluid from a hot space to a cold space and vice versa. The machine is said to have a thermal compressor and is sometimes called a thermocompressor. The variation in temperature at constant volume causes a change in pressure, (high when the fluid is in the hot space, low when it is in the cold space). The change in pressure is utilized in a separate but connected cylinder also containing a displacer to achieve refrigeration. The machine was devised by Rudolph Vuilleumier in 1918.

There are innumerable variations of Stirling engines some of which are set out in Figure 1. They involve displacer-piston and two piston versions and multiple piston arrangements and variations.

Vuilleumier engines are also found in a range of variations broadly classified as split systems or integral systems. In both the Stirling and Vuilleumier units a split system has the cold expansion space located in a separate cylinder remote from the hot compression cylinder and coupled to it by a single small-bore lead up to 2 m long.

3. Conclusion

Multiple applications for cryogenic cooling systems have resulted in the development of many different cryocoolers with different characteristics and attributes.

Some of the important requirements and the different types of unit are briefly reviewed.

4. References

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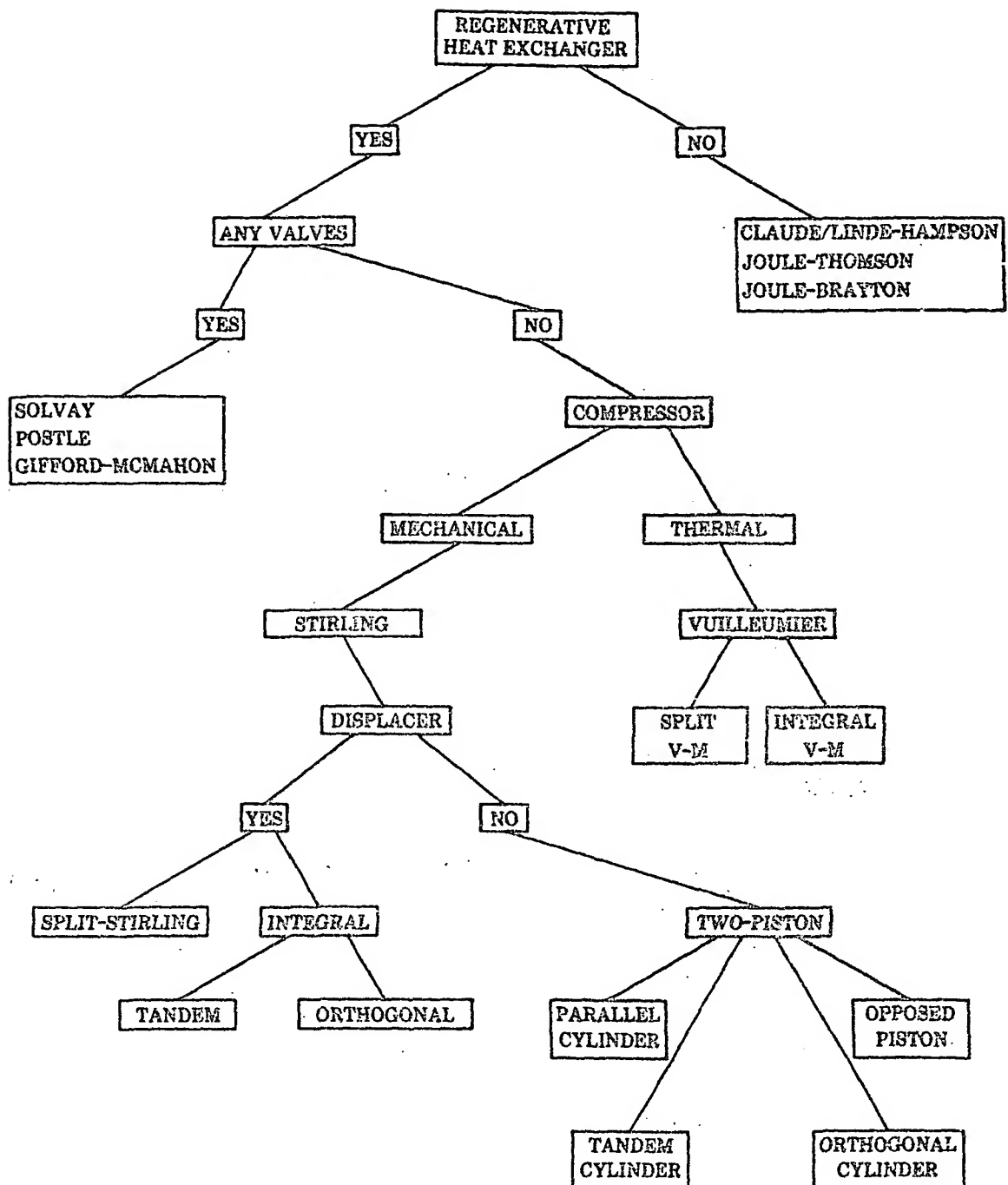


FIGURE 1. CLASSIFICATION OF CRYOCOOLERS